Earth Surface Processes and Landforms
Earth Surf. Process. Landforms **25**, 105–108 (2000)

SHORT COMMUNICATION

JÖKULHLAUP INITIATION BY ICE-DAM FLOTATION: THE SIGNIFICANCE OF GLACIER DEBRIS CONTENT

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Received 9 July 1999; Revised 15 October 1999; Accepted 18 October 1999

ABSTRACT

Ice-dam flotation is a commonly described mechanism for the initiation of jökulhlaups (catastrophic floods) from ice-dammed lakes, but predictions of the critical lake depth required for flotation often differ from the actual lake depth at which flotation occurs. Glacier debris content is identified as an insufficiently recognized variable in ice-dam flotation. It is demonstrated that high debris contents could suppress flotation, and thereby affect the timing, mechanism and magnitude of catastrophic lake drainage events. The density of the part of the glacier forming the ice dam (rather than pure ice density) is the key to predicting ice-dam flotation. Copyright © 2000 John Wiley & Sons, Ltd.

KEY WORDS: debris; density; flotation; ice-dam; ice-dammed lake; jökulhlaup

INTRODUCTION AND AIMS

Water bodies impounded by ice are common features of glaciated areas and their drainage is widely documented. The catastrophic floods or 'jökulhlaups' frequently associated with such drainage events can have a substantial impact on the physical environment (Shakesby, 1985; Sugden *et al.*, 1985; Russell, 1989, 1991; Desloges and Church 1992) and on human activity (Post and Mayo, 1971; Young, 1980, 1985; Ives, 1986; Desloges *et al.*, 1989; Björnsson, 1992). Where jökulhlaups occur, they do so on a fairly regular basis (Haeberli, 1983; Evans and Clague, 1994), the water level in an ice-dammed lake rising until a threshold is attained whereupon the lake drains through, over or under the retaining ice. Human activity is increasing in areas subject to such flooding (Sturm and Benson, 1985; Young, 1985) and the ability to predict the location, timing and magnitude of jökulhlaups is important, given the potential damage to life and property.

Of the eight types of ice-dammed lake drainage initiation mechanism commonly recognized (Tweed and Russell, 1999), flotation of ice dams by water impounded behind or beneath is one of the most important and widely invoked (e.g. Marcus, 1960; Stone, 1963; Lindsay, 1966; Sturm and Benson, 1985). The identification of the critical water depth at which flotation occurs should allow prediction of the timing and magnitude of lake drainage. Many researchers have attempted to predict dam flotation, but estimates have often been inconsistent with the water depth at which flotation has occurred (e.g. Lindsay, 1966; Moravek, 1973). This paper aims to improve our ability to predict ice-dam flotation by highlighting the potential importance of glacier debris content to this mechanism of ice-dammed lake drainage.

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CCC 0197-9337/2000/010105–04 $17.50

ICE-DAM FLOTATION

Rink (1897) and Rabot (1905) were amongst the first to theorize that jökulhlaups can be triggered by flotation of the ice dam and Thorarinsson (1939, 1953) discussed the mechanism in some detail.

The principles of ice-dam flotation are as follows. The density of glacier ice is usually between 0·83 and 0·915 g cm^{-3}, depending on the degree of ice compression (Röthlisberger and Lang, 1987; Paterson, 1994); however, a value of 0·9 g cm^{-3} is commonly assumed for glacier ice. On this basis, ice-dam flotation will occur when the lake water depth reaches 90 per cent of the height of the dam; this figure is widely cited when invoking flotation as an ice-dammed lake drainage mechanism. Thorarinsson (1939) stated that it is necessary to allow for any decrease in dam density due to crevasse frequency and that a greater depth of water may be required to effect flotation if the glacier is frozen to its bed. Knight and Russell (1993) proposed that ice dam thickness could decrease over the ablation season, flotation being triggered when the dam reaches 11 per cent of the lake water depth. However, a factor that has not been formally taken into account is the presence of rock debris in the ice dam, and the importance that this may have to ice-dam flotation and lake drainage.

THE IMPORTANCE OF DEBRIS

Most rock debris has a density greater than that of ice; typical values for rock density vary between 2 and 4 g cm^{-3}. Therefore a glacial dam containing debris requires a greater depth of water to effect dam flotation than is the case for a debris-free ice dam (excluding here other factors such as bed adhesion and crevassing). The precise level at which flotation occurs will depend on the density, concentration and distribution of debris in the ice dam.

Figure 1 illustrates the calculated lake depths at which ice-dam flotation occurs, for ice dams containing different concentrations and densities of debris. For example, assuming an ice density of 0·9 g cm^{-3}, and debris with a specific gravity of 3, an increase in the concentration of debris in the ice by 1 per cent (by

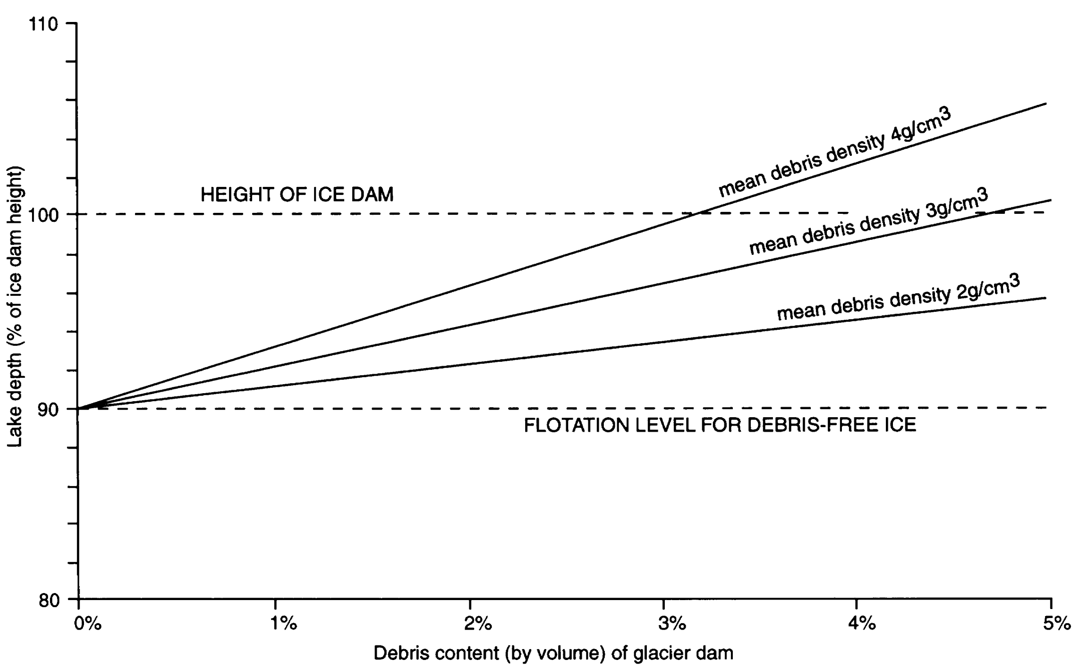

Figure 1. The depth of water theoretically required to float an ice dam containing different amounts of debris, for debris of different densities

volume) will increase the depth of water required to float the dam by 2·1 per cent (excluding bed-freezing and crevassing factors). Thus whereas debris-free ice floats at a water level of 90 per cent of the ice dam height, ice containing 1 per cent debris at 3 g cm^{-3} floats at a higher water level of 92·1 per cent. If the debris concentration is increased to 4·8 per cent, flotation is suppressed since the density of the dam is too great to float. Under these circumstances lake water overspills the dam as flotation cannot take place, the ice being effectively grounded.

DISCUSSION AND IMPLICATIONS

If a lake cannot drain by flotation before the water depth exceeds the height of the ice dam, this has implications for the initiation of other mechanisms of lake drainage, which require alternative methods of prediction (see Tweed and Russell, 1999). Should the lake reach a depth greater than 150–200 m before overspill occurs, then Glen's (1954) pressure-melting mechanism may be initiated. A shallower lake dammed by ice containing a high debris concentration could exceed the predicted depth for flotation and fill completely before overspilling. Similar critical thresholds relating to glacier debris content can be calculated for differing debris densities (see Figure 1). Thus, the presence of debris in an ice dam has consequences not only for the flotation mechanism, but also for the initiation of other drainage mechanisms if flotation is delayed or completely suppressed.

The size of the jökulhlaup could also depend on glacier debris content. For example, if the dam contains sufficient debris for flotation to be delayed until the lake water reaches 95 per cent of the height of the ice dam rather than 90 per cent, the outburst would be correspondingly larger. The morphometry of most lake basins ensures that proportionally greater volumes of water occur per unit increase in depth so that the increased volume of water released could be far greater than that implied by the percentage increase in water depth.

There are several cases in the literature where lakes have not floated ice dams at the supposedly 'critical' 90 per cent of the ice dam height. For example, Lindsay (1966) stated that Casement Glacier Lake, Alaska, rose to a level of 94 per cent of the ice dam before flotation occurred; these assertions were supported by Moravek (1973), although no reasons were given. Such situations may be attributable to the amount of debris in the ice, and it would be interesting to learn of flotation events for which there are reliable estimates of debris concentrations in the ice dam.

Cold-based glaciers have basal debris concentrations ranging from 0·01 to 70 per cent, with debris layers 10 m or more in thickness (Hambrey, 1994). Debris in some temperate and polythermal glaciers can constitute more than 50 per cent of the volume of basal ice (Boulton, 1975; Benn and Evans, 1998). Supraglacial debris can be substantial in glacier ablation zones and is characteristic of 'debris-mantled' glaciers in the Himalaya, the Andes and New Zealand (Kirkbride, 1995). Large amounts of debris can also be transported onto the surface of glaciers by mass movements (e.g. Post, 1967; Kirkbride and Sugden, 1992). Thus, there is the potential for ice-dam flotation to be affected by debris concentrations of the order commonly observable in some glaciers.

CONCLUSIONS

Conventional explanations of ice-dammed lake drainage initiation by flotation have neglected to examine the significance of glacier debris content. The concentration of debris in ice is intrinsic to glacier density and therefore crucial to the capacity for glacier flotation in lake water. By incorporating the density of the glacier forming the ice dam into predictions of flotation, it is argued that more realistic and reliable estimates of the timing and magnitude of jökulhlaups could be achieved.

Predictions of jökulhlaups from ice-dammed lakes are based on an understanding of the mechanism of the event. This paper has demonstrated that high debris content in glacial dams has the potential to affect (a) the mechanism, (b) the timing, and (c) the magnitude of drainage events, by increasing the depth of water required to float an ice dam, hence delaying flotation or suppressing it entirely.

ACKNOWLEDGEMENTS

Many thanks to Wilf Theakstone for his comments on the theoretical ideas contained within this paper, and to Peter Knight for discussions on the subject. Gratitude is also expressed to Tony Parsons who kindly read a much earlier draft of the manuscript, to Tim Harris for reading later drafts, to Danny McCarroll and a second anonymous refree for their constructive comments, and to Rosie Duncan for 'tidying up' the diagram.

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